National Aeronautics and Space Administration

YEARS 1-3 **EXECUTIVE SUMMARY**

# Dynamic Response of the Environment at the Moon (DREAM)

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NASA LUNAR SCIENCE INSTITUTE

# 5.1 DREAM 2012 Annual Report Executive Summary

While the Moon is often considered a stagnant "dead" body, it actually percolates with activity at the submicron and atomic levels; this activity animated by incoming solar energy and matter. In fact, the oxide-rich interface is in constant interaction with its environment, acting as an obstacle to inflowing solar plasma and continually releasing solar-stimulated atomic neutrals. These interactions create a super-surface layering about the Moon containing (1) a plasma interaction region that includes a near-surface plasma sheath and an extended, trailing solar wind plasma wake and (2) a neutral surface boundary exosphere and exo-ionosphere that extends hundreds of miles above the surface (see Figure ES.1). Apollo-era studies of these two systems revealed their presence and the tantalizing possibility of a very complicated and dynamic neutral-ion-volatile-plasma-dust environment.

NASA's Lunar Science Institute (NLSI) team called " Dynamic Response of the Environment At the Moon (DREAM)" is a lunar environment center consists of 12 expert

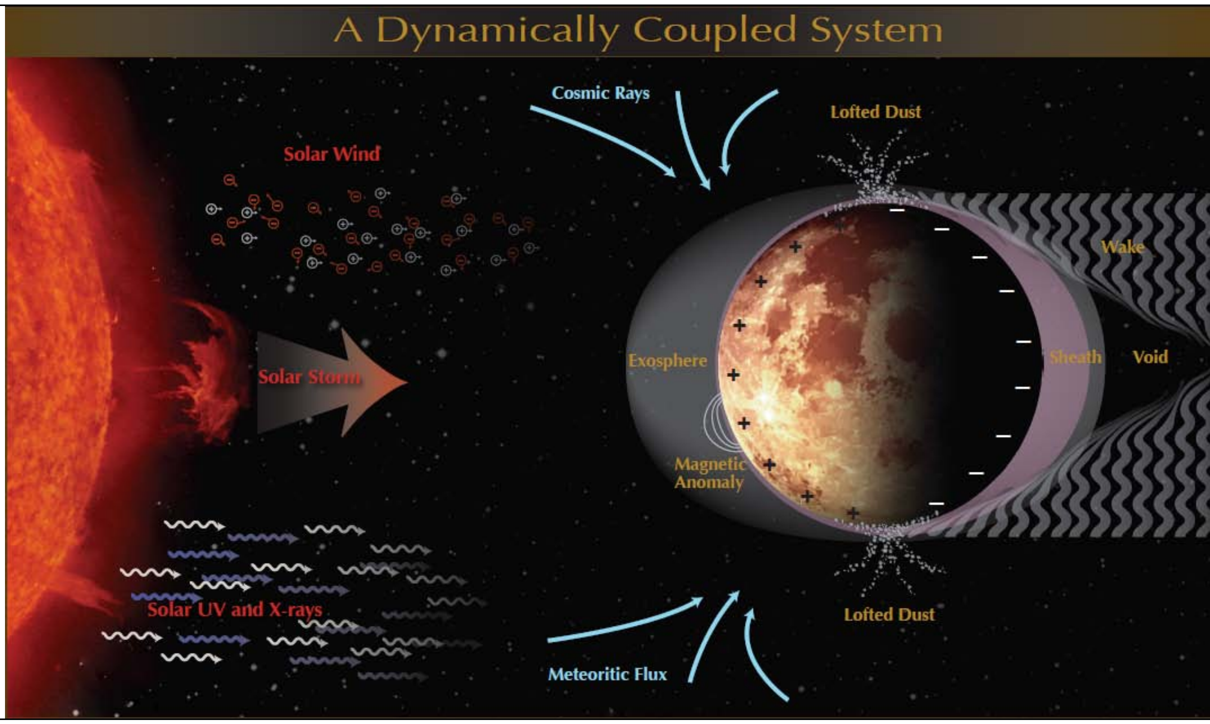


Figure ES.1: The solar-lunar connection studied by the DREAM lunar environment center

partners embarking on an advanced study of the surface-gas-plasma environmental systems at the Moon. The team especially examines how solar energy and matter affects the lunar surface (including the effect on surficial water, OH, Na, and other sequestered species), and in the understanding of the response of the surface to this solar energy input. DREAM's theory-modeling-data validation efforts explore the common linkages between plasma-neutral-surface system and to understand the system response during environmentally- extreme events like a passing solar storm or moderate sized, high velocity impact. DREAM EPO has a primary focus on advancing the teacher and student understanding of lunar extreme environmental conditions (i.e., the Lunar Extreme Program), such as the lunar surface reaction to solar-created coronal mass ejection and impacts/gas releases.

The DREAM lunar environment center addresses the fundamental question: **"How does the highly-variable solar energy and matter incident at the surface interface affect the dynamics of lunar volatiles, ionosphere, plasma, and dust?"** To answer this, DREAM has formulated 4 primary science objectives:

1. Advance understanding of the surface release and loss of the **neutral gas exosphere** over small to large spatial scales and a broad range of driver intensities.

2. Advance understanding of the enveloping **plasma interaction region** over small to large spatial scales and over a broad range of driver intensities.

3. Identify **common links** between the neutral and plasma systems and test these linkages by modeling **extreme environmental events**.

4. **Apply** this new-found environmental knowledge to guide decision-making for future missions, assess the Moon as an observational platform, and aid in human exploration.

In the first three year of DREAM, a number of key advancements and discoveries were made in each of these objectives. However, one of the most substantial and lasting contributions of the center is the integrated **Solar Storm/Lunar Atmosphere Modeling (SSLAM)** effort, where DREAM models where run in sequence to predict the behavior of a passing dense, heavy coronal mass ejection (CME) of plasma at the Moon. This modeling effort of the storm phenomenon was initiated in late 2009 and was capped by a week-long intramural workshop in mid-year 2011 where cross-connected model results were presented and dissected. In essence, the SSLAM effort was the completion of a key element of objective #3, where common links between the plasma, surface, and exosphere were examined in a period of extreme space weather: At a time period when existing links are accentuated by in the extreme plasma environment. While it is well-known that solar storms have an effect in the Earth's magnetic field and ionosphere (i.e., they are 'geo-effective'), solar storm effects at the Moon have not been previously examined.

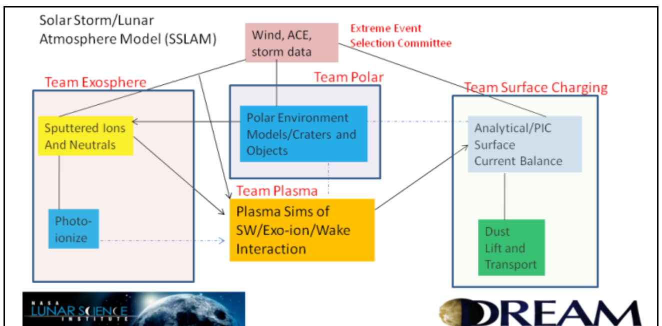

Figure ES.2 – Layout of the DREAM models used in the Solar Storm/Lunar Atmosphere Modeling (SSLAM) effort

Figure ES.2 shows the layout of SSLAM. An extreme event selection committee identified an ideal event for study: The intense Earth-directed CME on early May 1998. Plasma and radiation measurements from upstream monitors like ACE and WIND were then used as inputs to models of the lunar exosphere, polar environment, surface charging, and lunar surface-plasma interaction. Key finds include the following: 1) During a CME passage, the exposed lunar surface receives an increase in mass flux from the exogenic CME driver plasma of about 300 tons. 2) However, this same intense driver plasma containing large concentrations of heavy multi-charged ions can liberate atoms from the regolith via sputtering, releasing 100-200 tons of atomic/molecular material over the 2-day CME passage. 3) The lunar exosphere is thus expected to become enhanced or 'bulked up' during a CME passage due to sputtering (see Figure ES.3). 4) Sputtered ions also populate the near-Moon environment and there is a general increase in CME plasma ions reflected upstream - the combination acting to slow down the driver plasma. 5) Anomalous surface charging effects occurred, including the release of originally-trapped dayside photo-electrons (due to a reduction in the trapping surface potential) and anomalous ion inflows into polar craters with local sputtering acting as a source of volatile loss.

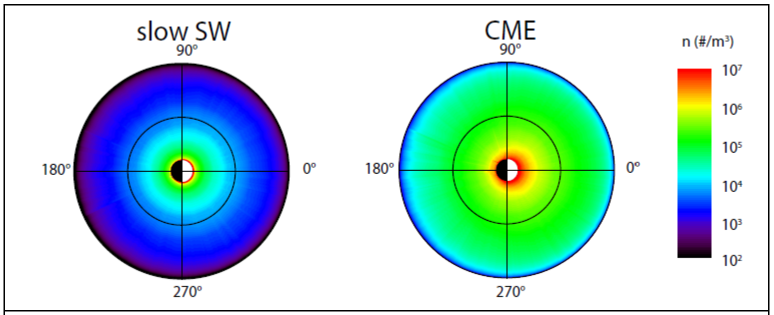

Figure ES.3- The enhancement in the sodium exosphere from CME sputtering (from Killen et al. 2012).

This SSLAM effort cross-integrates individual DREAM models to form a larger system-level model of the environment. Such an overarching endeavor involving over 30 people and integrating 10 independent models could simply not be constructed via a single or even multiple LASER awards – it truly requires an institute formed with the proper personnel, data, and modeling tools to perform the job.

The **SSLAM effort was a focal point of DREAM E/PO activity**. Two high schools, Eleanor Roosevelt in Greenbelt MD and Seton-Keough in Baltimore MD, had students participate the DREAM's Lunar Extreme Program: a 16-week online class and webinar series featuring a set of teaching exercises and lectures on solar/space weather at the Moon (see syllabus at http://ssed.gsfc.nasa.gov/dream/DREAM/syllabus1.html). This program culminated in student participation in the DREAM SSLAM workshop in June 2011.

Another key advancement made by DREAM team members and shared with our sister institution, the Colorado Center for Lunar Dust and Atmosphere Science (CCLDAS), is the **discovery of a precursor plasma layer ahead of the Moon**. Prior to the NLSI, the conventional wisdom was that the solar wind ions and electrons incident directly on the dayside lunar surface were complete absorbed by the surface, leaving a trailing void in the flow behind the Moon (i.e., commonly called the lunar wake). From a philosophical perspective, he lack of a lunar precursor layer has been considered troubling since objects in a flowing plasma naturally tend to transmit upstream information (i.e., plasma waves) into the flow.

However, Dr. Andrew Poppe, performing his graduate work under CCLDAS (at the University of Colorado) developed a set of provocative plasma simulations of the dayside plasma sheath region that clearly showed the development of a new electrostatic layer lying at heights above the dayside photo-electron sheath. This layer had the ability to both reflect incoming solar wind electrons and accelerate some of the cold photoelectrons outward from the Moon. Simultaneously, DREAM co-I Berkeley's Dr. Jasper Halekas was reporting the detection of unusual beams and anomalous reflected electron distribution from the Lunar Prospector MAG/ER instrument. The two recognized that each had a key piece of information and started a strong collaboration with Dr. Poppe eventually becoming a DREAM post-doc at UCBerkeley. Since that time, they have confirmed the presence of a lunar plasma precursor layer using ARTEMIS observations (in one case detected > 8000 km from the Moon). The plasma layer is similar in nature to the terrestrial foreshock region ahead of the Earth's bow shock and is a source of plasma turbulence that is attempting to slow/alter the incoming solar wind electron population. Indeed, the Moon does transmit information into the upstream plasma; this to indicate its presence and to divert & slow the incoming fast solar inflow.

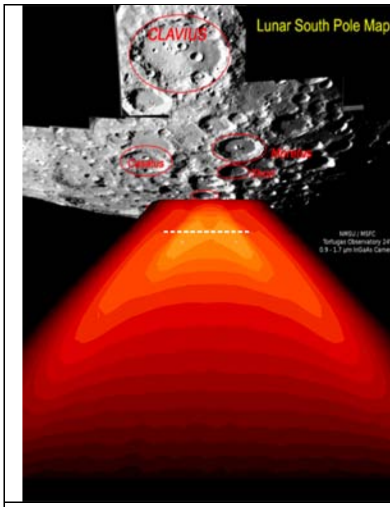


Figure ES.4- A model of the LCROSS sodium plume (Killen et al., 2010)

While the advances above demonstrate the team's large-scale coherent modeling efforts and center-to-center collaborations, a third DREAM advance demonstrates the team's innate ability to immediately respond to new events. Specifically, DREAM Co-I Rosemary Killen was able to obtain time on the **Kitt Peak Telescope to observe the 2009 LCROSS impact** with the sensitive 589 nm sodium D-line filter. Unfortunately, the initial opportunity lacked funding for both investigator labor time and travel. However, DREAM resources, in the form of a block grant located at GSFC, could be easily redirected to fully exploit this unplanned opportunity. In fact, to solicit support from HQ was simply not possible: the submission of a LASER proposal would have been reviewed and awarded long after the LCROSS encounter. This investigation in particular highlights a clear advantage of an institute-type award: Resources are more easily accessible and available to the working 'boots-on-the-ground' scientists.

The observation campaign occurred during clear skies and was very fruitful, providing the only ground-based observation of the LCROSS impact. In fact, impact-ejected sodium from the bottom of Cabeus crater was observed to diffuse for up to 9 minutes after the impact. Comparing Monte Carlo models of the Na release (like Figure ES.4) to the telescopic observations suggest that the impact temperature for the species was near 1000K. This information provided critical and independent support to the LCROSS team who also arrived at a similar temperature.

As evident, **DREAM topics tie into many of the cross-cutting themes defined in the Vision and Voyages Planetary Decadal study** [Nat. Acad. Press, 2011]. The DREAM lunar environment center has an emphasis on the variable solar-lunar chemical and physical surface processes, and thus connects directly to the Decadal's Working of the Solar System Theme #9 [Planetary Atmospheres] and #10 [Basic Chemical and Physical Processes]. However, DREAM's emphasis on volatile migration and solar wind/surface interactions also ties it to the Building New Worlds Theme #3 [Supply of Water] and Planetary Habitats Theme #4 [Modern Organic Synthesis]. A key Decadal theme is the role of water and organics in the building of new worlds. In 2009, LCROSS and $M^3$ observations indicate that the Moon harbors and possibly actively transports water and OH. DREAM team members formed a cross-center focus group with other NLSI teams to further advance the understanding of 1) water migration from poles to mid-latitudes, 2) the manufacturing of OH and water from implantation of the solar wind protons into oxygen –rich regolith and 3) the expectations for LADEE to observe the evidence of water and OH transport. DREAM team members gave key invited talks at the Wet vs Dry Moon workshop and at LPSC on water migration and manufacturing. We also provided new insights on solar wind ion flow into polar craters; such ions possibly being a sputtering loss process of key volatiles in these regions.

In the latter part of our DREAM studies, we now consider the possibility that all exposed rocky bodies may be prime targets for new reactive chemistry from the space environment. For example, DREAM models were recently adapted to small bodies to infer whether the colder, partially lit regions of Vesta could harbor volatiles. We now consider that even the 'deadest' of rocky bodies may be slowly manufacturing new molecules via reactive chemistry triggered by solar wind implantation. This concept becomes our new cross-cutting question: Do all exposed rocky bodies manufacture and harbor OH and water? Given an exposed body's continual irradiation by the solar wind and extended exposure to the space environment, that possibility has to be entertained, consistent with the cross-cutting Decadal themes on water, organic synthesis and physical/chemical processes (i.e., Themes #3, #4, and #10).

DREAM team members were also active in **'Supporting Other Institute Objectives (SOIO)'**. DREAM Participated in a number of E/PO events including Maryland Day 2009, 2010, and 2011 at the University of Maryland Campus. DREAM's E/PO team also took a leading role in the formation and implementation of the International Observe the Moon Night. DREAM joined with GSFC's Lunar and Planetary Space Academy on lunar projects for undergraduate science and engineering majors in the summer of 2009-2011. The IT team continued to enhance the DREAM webpage that describes our lunar science (http://ssed.gsfc.nasa.gov/dream/). DREAM E/PO lead Lora Bleacher and Collaborator Noah Petro initiated a new group call the 'Next Generation Lunar Scientist and Engineer (NGLSE)' to engage and develop the next generation of lunar scientists and engineers, and to enable their successful involvement in current planning for the scientific exploration of the Moon. DREAM team members continue to be active participants in NLSI's Dust and Atmosphere Focus Group which advocates for lunar science that especially emphasizes dusty exosphere and plasma research. Team members continue to be recognized as science leaders by chairing conference sessions at LDAP2010, LSI-Forum, and LPSC. DREAM press releases and web-features are consistently picked up by the mainstream media and distributed widely, including releases on the electrical lunar polar craters (http://www.nasa.gov/topics/moonmars/features/electric-craters.html), sodium LCROSS ground-based observations (http://www.nasa.gov/mission_pages/LCROSS/news/lunar-water-metal.html), dust-generated electrons (http://science.nasa.gov/science-news/science-at-nasa/2011/14nov_lunarionosphere/), solar storm/lunar atmosphere enhancement (http://www.nasa.gov/topics/solarsystem/features/dream-cme.html) and volatiles at Vesta (http://www.nasa.gov/mission_pages/dawn/news/dawn20120125.html).

Figure ES.5- DREAM's Mike Collier at Maryland Day

To summarize, the DREAM lunar environment center provides uninterrupted coherency for its researchers, allows immediate reaction & resource deployment to act on new events and finding, and fosters the spirit of community-level cooperation that extends well beyond the boundaries of its own center. All total in the DREAM center's first three program years, the team has 35 science papers submitted to referred journals, provided > 130 talks/presentations at conferences like AGU, Lunar Science Forum, & LPSC, and have mentored over 18 high school and undergraduates via DREAM's Lunar Extreme Program and GSFC's Lunar Planetary Space Academy. The team has initiated > 40 lunar-related investigations that interconnect team members, connect across to other NLSI teams, and link to the international lunar community.

# DREAM

Dynamic Response of the Environment at the Moon

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